



THE ROLE OF NITROGEN FIXATION AND NUTRIENT SUPPLY IN SOME AGROFORESTRY SYSTEMS OF THE AMERICAS

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(Accepted 3 September 1996)

Summary—There are a large number of agroforestry systems practiced in the Americas in which nitrogen-fixing trees are used to supply nitrogen and organic matter as well as to make other contributions to improve growth conditions for non-nitrogen-fixing components, including annual crops, perennial crops or animals. These systems can be divided into traditional systems, whose origins were before the European conquest of the Americas, natural systems which may have existed previous to human occupation of the Americas about 20 000 years ago, and systems devised by agricultural scientists in the last 100 years. An attempt is made to evaluate nitrogen fixation and the source of nutrients in over 10 such traditional and synthetic systems. Controlled experiments over a sufficient time to establish an accurate picture of nitrogen fixation and decomposition of organic residues generally are lacking. Systems with low nutrient removal, in which trees are allowed to grow for long periods without being pruned, would be expected to make greater contributions to the improvement of soil conditions. Measurements from systems such as shaded plantations and alley farming, in which trees are frequently pruned and rates of removal of nutrients is high, generally show only a slow buildup of nitrogen, soil organic matter, levels of available nutrients and improvements in soil physical conditions. Perhaps nonequilibrium conditions from pruning, burning and nutrient removal in crops lead to faster accumulation of nutrients through nitrogen fixation and other processes characteristic of “stressed” systems. The success of agroforestry systems may be favored by the maintenance of such nonequilibrium conditions. © 1997 Elsevier Science Ltd

INTRODUCTION

Many of the trees used in agroforestry systems have been shown to fix atmospheric N₂, and thus may contribute nitrogen to the system. However, the amounts contributed will depend on the same factors which limit nitrogen fixation in other contexts (limited nutrient supply, inappropriate symbionts, nodule effectiveness and activity, moisture supply, presence of inhibitors such as combined nitrogen, etc.) (Giller and Wilson, 1991). Other factors may affect the transfer of nitrogen from the nitrogen-fixing component to non-nitrogen-fixing components of the system. Such factors are decomposition rates of above and below ground plant parts, demand for nitrogen by soil microorganisms, denitrification, leaching, volatilization, and the ability of the non-nitrogen-fixing component to compete for the N released.

This complexity may explain why nitrogen-fixation measurements in agroforestry systems tend to vary widely (Danso *et al.*, 1992). Transfers within

the system invariably involve losses of nitrogen, because the degree of nutrient cycling among components of natural forest ecosystems is rarely attained in man-made agroforestry systems (Nair *et al.*, 1995). The system that has been most extensively studied is the shaded perennial crop system (principally coffee and cacao). Nitrogen-fixing shade trees were shown to reduce nitrogen losses by leaching, but they may establish more favorable conditions for denitrification of applied mineral nitrogen (Babbar and Zak, 1994, 1995). Pruning of trees often results in death of nodules, leaving the tree unable to fix nitrogen and dependent on nitrogen from other sources for several weeks following pruning (Danso *et al.*, 1992; Nygren and Ramirez, 1995). Leaf decomposition patterns probably favor reabsorption of nitrogen by the same species rather than transfer to another species (Nair *et al.*, 1995).

Similar constraints may be more or less operative in other agroforestry systems, in which transfer of nutrients among components has been less studied. In silvopastoral systems, the nitrogen-fixing component is often consumed by animals, and nitrogen-fixing components may vary in their response to

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repeated defoliation (Stuer *et al.*, 1994). Recovery of nitrogen from the animal will vary with management practices. Transfer of nitrogen from nitrogen-fixing woody components to non-nitrogen-fixing nonwoody components is limited, as nutrient release patterns from legumes rarely coincide with uptake patterns by the crops (Haggar *et al.*, 1993).

In other agroforestry systems, such as taungya (growing annual agricultural crops along with forestry species during the early years of establishment of the forestry plantation) (Nair, 1993) or border plantings of trees for timber or fuelwood, nutrient transfer is probably not critical and has not received much attention in systems such as rotational plantings of *Acacia mangium*, where crops are planted following timber harvest. Total soil nitrogen was found to increase after 3 y under pure stands of *Acacia mangium* and *Inga edulis*, but not under *Stryphnodendron macrostachyum*, *Pithecellobium macradenium* and *Pentaclethra macroloba* on a high aluminum soil in Costa Rica (Fisher, 1995).

Supply of nutrients other than nitrogen in agroforestry systems has received somewhat less attention, although phosphorus often has been considered to be limiting in such systems. Improving phosphorus availability through mycorrhizal inoculation is often more effective than mineral P applications (Danso *et al.*, 1992); interactions of P with biomass may be quite complex (Paniagua *et al.*, 1995). A rational basis for supplying nitrogen and other nutrients to non-nitrogen-fixing components of agroforestry systems is inadequately developed, but fortunately research interest in this area has increased recently.

For discussion, agroforestry systems of the Americas will be divided into two groups: traditional systems, which have been used for 100 years; and newly devised systems, which have been practised following suggestions of scientists. Under traditional systems, we shall consider shaded plantation systems, home gardens, shifting cultivation, improved fallows and traditional silvopastoral systems. Newly devised or "synthetic" agroforestry systems began with the development of taungya in Burma (now Myanmar) in the mid-19th century, and these were followed by border plantings, alley farming, protein banks and rotational woodlots (Nair, 1993).

Giller and Wilson (1991) have reviewed the contribution of nitrogen fixation to tropical cropping systems, and they cited considerable differences in nitrogen fixation by different tree species and encountered analytical problems in determining the amount of N fixed in such systems. Peoples and Herridge (1990) summarized the reports of N fixation studies by different woody legumes, and found a range of measurements from less than 12 kg ha⁻¹ y⁻¹ for *Acacia holostera* in Senegal to

934 kg ha⁻¹ y⁻¹ for *Leucaena leucocephala* in Malaysia. These measurements were made with ¹⁵N, considered more reliable by these authors than the acetylene reduction assay (ARA) used in four of the eight studies they reviewed.

The population of nitrogen-fixing trees will affect the amount of nitrogen fixation. A shade system with fewer than 100 nitrogen-fixing trees ha⁻¹ will fix less nitrogen than *Mimosa scabrella* or a protein bank of *Erythrina poeppigiana* with 10 000 trees ha⁻¹. The amount of nutrient removal will depend upon the crops produced. However, a stressed system in which the amount of nutrient removal is high may support more total fixation and mobilization of other nutrients than a solid planting of nitrogen-fixing trees, which may subsist on a low supply of nutrients for several years. The presence of animals in the system will also affect nutrient demand and cycling. Pruning regimes, the amounts of nutrients applied and present in the soil, and the use of the prunings will affect nitrogen fixation. Generally, the potential for nitrogen fixation will depend upon the presence or absence of leguminous or actinorhizal trees for which nodulation and nitrogen fixation have been proved. A whole system has been measured by Jensen (1993b); it is possible in these systems that some fixation by nonsymbiotic organisms or endophytes occurs.

THE ROLE OF NITROGEN FIXATION AND NUTRIENT SUPPLY IN TRADITIONAL AGROFORESTRY SYSTEMS OF THE AMERICAS

Shaded plantation systems

Shaded plantation systems are probably the most important agroforestry systems of the Americas. Cacao has been grown under shade since its domestication (Budowski *et al.*, 1984). The Aztec word for *Gliricidia*—cacahuanantl, literally "cacao mamma"—indicates that this genus was associated with cacao in pre-Columbian America, (Ford, 1987). When coffee was introduced into the Americas in the 18th century (Grigg, 1974), it invariably was grown as a shaded crop. Other crops frequently grown under shade or with leguminous trees for support are vanilla, black pepper, tropical yam, various spice trees, and tobacco for cigar wrappers.

There is a wide range of management practices in these systems. Plantations may be heavily fertilized with nitrogen and other elements (Fassbender, 1993) or not fertilized at all (Herrera *et al.*, 1987). Populations of leguminous trees for shade vary widely from fewer than 100 to as many as 300 trees ha⁻¹. Pruning regimes may vary from no pruning to several prunings a year, in which all prunings of the leguminous component are placed on the ground. These practices will affect how much nitrogen is fixed by the leguminous com-

ponent and how much becomes available. In a variant of this system a leguminous cover crop is used in conjunction with a nonleguminous perennial. Nitrogen fixation in several such systems has been estimated at approximately $150 \text{ kg ha}^{-1} \text{ y}^{-1}$, considerably higher than the amounts generally attributed to leguminous shade tree systems (Giller and Wilson, 1991). Nutrient losses may be less under such systems, and if cattle graze they will reduce its height and competition with the trees. Such systems probably are more characteristic of Asian than American plantations.

Almost all measurements of nitrogen fixation in shaded coffee and cacao plantations have used the acetylene reduction assay (Escalante *et al.*, 1984; Roskoski and Van Kessel, 1985; Lindblad and Russo, 1986). It may underestimate N_2 fixation, as it is a short-term measure of nitrogenase activity (Peoples and Herridge, 1990). Lindblad and Russo found that rates of acetylene reduction in a heavily fertilized coffee plantation, shaded with *Erythrina poeppigiana*, were similar to those Roskoski and Van Kessel (1985) and Escalante *et al.* (1984) found in unfertilized coffee and cacao plantations shaded with *Inga juncuifol*, *Gliricidia sepium* and *E. poeppigiana*. Transfer of nitrogen from the leguminous shade tree to the non-nitrogen-fixing associated crop has generally been assumed to come largely through the prunings and litterfall which for *E. poeppigiana* can amount to $12 \text{ t ha}^{-1} \text{ y}^{-1}$ of dry matter, containing more than 300 kg of nitrogen (Fassbender, 1993). Escalante *et al.* (1984) found that in a cacao plantation shaded by an unpruned mixture of *E. poeppigiana*, *Artocarpus altilis* and *Castilloa elastica*, total litterfall contained $321 \text{ kg ha}^{-1} \text{ y}^{-1}$ of N while nodule N accumulation averaged $22.3 \text{ kg ha}^{-1} \text{ month}^{-1}$ in an unfertilized plot and $22.5 \text{ kg ha}^{-1} \text{ month}^{-1}$ in a plot fertilized with 9, 9 and $12 \text{ kg ha}^{-1} \text{ y}^{-1}$ of N, P and K, respectively. Escalante *et al.* (1984) calculated a nitrogen release of $57\text{--}66 \text{ kg ha}^{-1} \text{ y}^{-1}$ through nodule senescence and decomposition. Total N in the soil to a 60 cm depth was 35 t ha^{-1} .

In a study of a pure *E. poeppigiana* plantation, with a somewhat higher tree population than is generally used in cacao or coffee plantations ($625 \text{ trees ha}^{-1}$), Nygren and Ramirez (1995) found a nitrogen turnover of $6.8\text{--}35.4 \text{ g}$ per tree in a 23 wk pruning cycle ($9.6\text{--}50.0 \text{ kg ha}^{-1} \text{ y}^{-1}$) through nodule senescence and decomposition. Nodules disappeared almost completely for 10 wk following pruning. Nodule population was highest about 14 wk after pruning (Fig. 1). There was a considerable difference between clones of *E. poeppigiana* with respect to nodule numbers. Although this study confirms the importance of a below-ground pathway of N transfer from nitrogen-fixing to non-nitrogen-fixing plants, there also may be 20 wk in the year during which the leguminous tree is not fix-

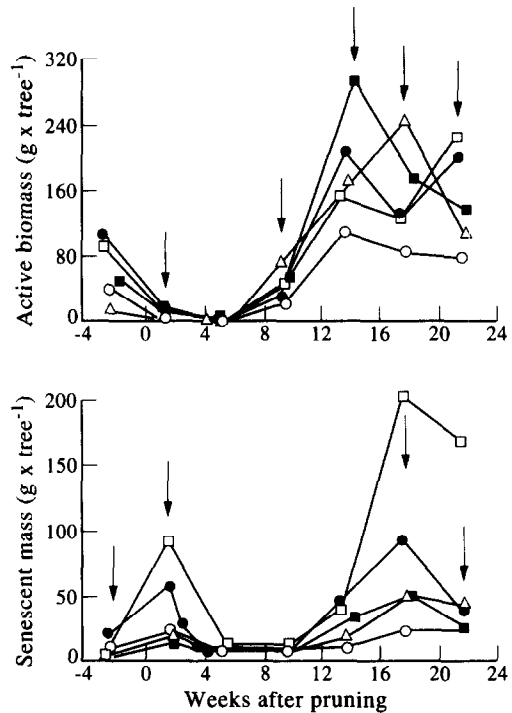


Fig. 1. Development of the average standing crop of active (top) and senescent (bottom) nodules in four clones and a half-sib family (2431) of *Erythrina poeppigiana* during a pruning cycle of 23 wk. The pruning was carried out on 12 June 1992. Statistically significant differences (Duncan's MRT at 5%) between tree sources were obtained in samplings marked with arrows (Nygren and Ramirez, 1995). Clone symbols as follows: ■ 2431; □ 2660; ● 2662; ○ 2687; △ 2693.

ing nitrogen and is competing with the non-N-fixing component for soil N. Van Kessel *et al.* (1994) used the natural ^{15}N abundance method to measure transfer of N from *Leucaena leucocephala* to unspecified understory vegetation. Although they found evidence of rapid transfer, they noted that because the isotopic concentration of N changes during various biological processes, the value of this method as a quantitative tool for measuring N transfer in different ecosystems may be severely limited.

Nitrogen-fixing shade trees generally function well in supplying N and K to shaded crop systems, but there is some evidence that certain non-nitrogen-fixing trees may be better in recycling Ca and Mg in such systems (Glover and Beer, 1986; Szott and Kass, 1993). Imbach *et al.* (1989) found much greater leaching losses of Ca, Mg and K under *Theobroma cacao* + *E. poeppigiana* than under an association of *T. cacao* with the non-nitrogen-fixing *Cordia alliodora*. Alpizar *et al.* (1986) showed that the *Cordia* system with its a greater biomass of fine-roots captured more nutrients from the soil. Cycling indices (relation of nutrient turnover to nutrients in standing biomass) were higher in the *Erythrina* systems (Beer *et al.*, 1990; Nair *et al.*, 1995). Nutrient cycling may be less "tight" in the

systems where frequently pruned nitrogen-fixing shade trees contribute biomass with high N to the soil surface, where it may be subjected to leaching and volatilization loss of N. Babbar and Zak (1994, 1995) showed that shading reduced leaching losses in a Costa Rican coffee plantation fertilized with mineral nitrogen, although evolution of N_2O was higher in the shaded than the unshaded plantation. Less fine root biomass, important in nutrient cycling, was found in coffee and cacao shaded with *Erythrina* than when shaded with *Cordia* in experiments at CATIE (Nair *et al.*, 1995). It should be pointed out that in the studies with *Erythrina* and *Cordia* at CATIE, the *Erythrina* was pruned while the *Cordia* was not.

The lower fine-root biomass under *T. cacao*–*E. poeppigiana* was probably caused by the fine-root turnover following the pruning of *E. poeppigiana*. Under humid conditions, periodic prunings have been observed to check fine-root growth both in *E. poeppigiana* (Nygren and Campos, 1995) and several other leguminous tree species (Hairiah *et al.*, 1992). Abundant fine-root biomass may explain the apparently high nitrogen-cycling capacity of *Senna* which apparently does not fix nitrogen (Danso *et al.*, 1992). *Senna* does not live as long as *Inga* or *Erythrina* when used as a coffee shade.

Home gardens

Agriculture in the Americas may have begun with germination of discarded seeds around settlements. Mixtures of useful crops around the homestead remain an important feature of agriculture in the Americas and especially in the Yucatan of Mexico. The so-called terra preta do indio soils of the Brazilian Amazon are now generally accepted to be Oxisols which have been altered by the accumulation of household wastes and other plant and animal residues in such a system (Zech *et al.*, 1990). There have been some studies of nutrient cycling in such systems in Asia, but none in the Americas. The type of study that is required is shown in Fig. 2, taken from Jensen (1993a,b) who measured nitrogen fixation in a Javanese home garden using the ARA assay and obtained an estimate of $18 \text{ kg ha}^{-1} \text{ y}^{-1}$. Measurement would include both symbiotic and nonsymbiotic nitrogen fixation. Zech *et al.* (1990) have shown evidence of nutrient accumulation over time in Mexican home gardens on a Typic Chromustert (Table 1). The authors also showed that the use of animal manures in such systems leads to a greater accumulation of aromatic organic compounds and stabilization of the organic matter.

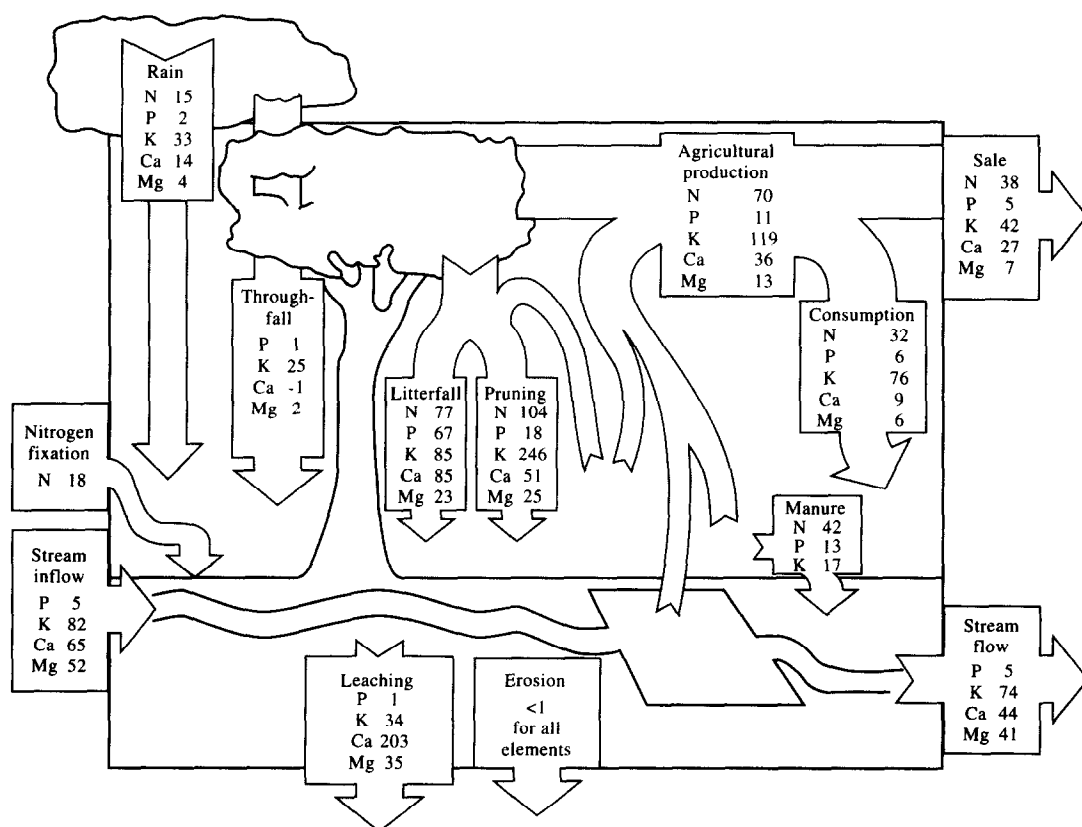


Fig. 2. Annual nutrient fluxes in a homegarden ecosystem at Legokole, West Java, Indonesia ($\text{kg ha}^{-1} \text{ y}^{-1}$) (from Jensen, 1993b).

Table 1. Characterization of the surface soils (0–10 cm) near Oxkutzab, Yucatan, Mexico (Zech *et al.*, 1990)

Land use	Sand (%)	Silt (%)	Clay (%)	pH (CaCl ₂)	Organic C (g kg ⁻¹)	Pore volume (%)
Secondary forest	4	46	50	6.4	28.7	67
Young tree garden	3	41	56	6.9	17.7	62
Mature tree garden	4	41	56	7.5	24.8	62
Corn field	4	39	56	7.1	22.0	63
Compost bed	5	39	56	7.3	28.7	69

Shifting cultivation

The importance of nitrogen fixation in shifting cultivation will depend on the proportion of nitrogen-fixing trees in the vegetation cut and burnt. A forest fallow will also serve to entrap nitrogen from dust and precipitation. There may be considerable remobilization of elements into more available forms during the fallow period and the burn following fallow. Grigg (1974) distinguishes two types of shifting cultivation in the Americas, the *roça*, with a long forest fallow, and the *barbecho*, with a short fallow. In both systems, the area is burned following clearing and before planting of crops. Grigg (1974) maintained that in 1974 about a fifth of the cropland in Mexico was still prepared by slash and burn methods. Two types of shifting cultivation systems of the Americas are: the milpa, in which maize predominates, and the conuco, in which most crops are roots and tubers, propagated vegetatively. Most agroforestry systems developed as an intensification of the shifting cultivation system (Raintree and Warner, 1986). In the Peruvian and Brazilian Amazon, even in the *roça* system, land is not fully abandoned after the cropping period but species persist, especially trees, that are used during the fallow period (Padoch and De Jong, 1987; Unruh, 1990; Kass *et al.*, 1993). How much nitrogen may be fixed by a forest fallow? Sanchez (1976) presents data that a secondary forest may accumulate 600 kg ha⁻¹ of nitrogen in its first 5 y, of which Kass and Drosdoff (1970) estimated that up to 60 kg ha⁻¹ y⁻¹ could come from symbiotic nitrogen fixation and another 60 kg ha⁻¹ y⁻¹ could come from nonsymbiotic fixation in the phyllosphere, rhizosphere, litter and blue-green algae on the soil surface. Sanchez (1976) points out that these rates of nutrient accumulation are unlikely to be maintained for more than 8 y, after which nutrients would recycle within the system. Vitousek and Sanford (1986) give values of 32–1980 kg ha⁻¹ of N in a range of moist tropical forests. They note that soil type will greatly affect the rate of nitrogen accumulation.

Improved fallows

Leguminous trees and shrubs may be of great importance in the *barbecho* type of shifting cultivation, where fallow periods are generally shorter. Two of the traditional fallow systems (Kass *et al.*, 1993) are based on leguminous trees, *Mimosa tenuiflora* Willd. and *Mimosa scabrella* Benth. Allen and

Allen (1981) confirm nodulation in *M. tenuiflora*, while Döbereiner (1984) reported a considerable increase in the nitrogen content of *M. scabrella* seedlings in response to modulation. *M. scabrella* has been successfully introduced into the acid soils of Mexico as a shade for coffee plantations. Kass *et al.* (1993) presented some indirect evidence for enrichment of soil organic matter and Ca, Mg, and P concentrations following a *M. tenuiflora* fallow. *M. tenuiflora* grows well in the shallow, rocky soils of the Pacific slope of Central America. It should also be noted that there are fallow systems involving palms such as *Orbygnia phalerata* which may harbor other endophytic nitrogen-fixing organisms (Kass *et al.*, 1993). Staver (1989) and Szott *et al.* (1991) experimented with a mixed *Inga-Desmodium* fallow in the Peruvian Amazon; both of these species should contribute nitrogen to the system. However, after about 36 months nutrient stocks in soil, living biomass and litter began to decline for N, K, Ca and Mg but not for P. Szott *et al.* (1991) suggest high leaching losses (2200 mm annual rainfall and precipitation exceeding evapotranspiration for 9 months of the year) were responsible for the failure to accumulate nutrients after 36 months. Possibly without nutrient removal, equilibrium was established, and there was no further accretion of nutrients to the system. Sanginga *et al.* (1994) reported that *Gliricidia sepium* derived a greater proportion of its nitrogen from biological fixation when pruned than when unpruned.

Traditional silvopastoral systems

The introduction of grazing animals to the Americas by European settlers led to the development of animal production systems based to varying degrees on browsing of trees. In areas with prolonged dry seasons, nitrogen-fixing trees may provide an important source of nutrients when moisture is insufficient for the growth of grasses. At least six such systems have been described: the espinales of Chile, Bolivia and Argentina (Ovalle *et al.*, 1990); the chaco of Argentina, Bolivia and Paraguay (Mazzarino *et al.*, 1991); the caatinga of Northeastern Brazil (Kirmse *et al.*, 1987); the tacotalles of Central America (Kass *et al.*, 1993), the cer rado of Central Brazil (Eiten and Goodland, 1979), and the matorrales of Northern Mexico (Medellin-Leal and Gomez-Gonzalez, 1979; Stienen, 1990). Leguminous trees and shrubs are an important component of the vegetation of all of these systems,

and contribute to the nitrogen economy. All of the most important genera (*Miniosa*, *Prosopis*, *Acacia*, *Pithecellobium*) nodulate and fix nitrogen (Döbereiner, 1984). Besides animal grazing and browsing, there is generally a cropping phase in which areas of scrub vegetation, to some degree enriched by animal manures, are used for annual cropping for 1 or more years until fertility declines, soil physical properties degrade, and weed control becomes difficult. Thus the cropping area of perhaps 2 ha is rotated over an area of perhaps 20 ha during a 20–50 y period. The animals also eat crop residues, ingest the seeds of leguminous trees and aid in their scarification and dispersion. Ovalle *et al.* (1990) have speculated that the espinal system might have functioned with camelloids such as the guanaco prior to the introduction of European ruminants, giving evidence that the chief leguminous shrub of this system, *Acacia caven*, may have been introduced to the espinales by the guanaco about 1000 years ago. Janzen and Martin (1982) have speculated that horses are presently aiding in the dispersion of the nonleguminous *Crescentia alata* in the Central American tacotales in the same way as Pleistocene horses.

There have been frequent efforts to improve the management of these systems to make them more productive and sustainable as overgrazing is frequently a problem, leading to the elimination of the leguminous trees and shrubs (Eiten and Goodland, 1979; Stienen, 1990; Ovalle *et al.*, 1990; Mazzarino *et al.*, 1991). Kirmse *et al.* (1987) evaluate positively a traditional practice in which the caatinga vegetation is clearcut at the beginning of the rainy season, resulting in a higher herbaceous population in the rainy season, but better quality woody browse in the dry season. Tiessen *et al.* (1992) provided evidence of changes in the form of P during the fallow. Selective cutting of woody shrubs such as *Prosopis* is recommended in the Argentine chaco to maintain the *Prosopis* in the grazed areas (Mazzarino *et al.*, 1991). Effects of the presence of *Prosopis* on nitrogen balance in the Argentine chaco is shown in Table 2. *Prosopis* is considered a weed in the southwestern U.S., where it competes with more productive pasture

grasses (Herbel, 1979). Introduction of fruit and timber trees into the silvopastoral system without eliminating the leguminous trees and grazing animals has been successful in the matorrales of northeastern Mexico (Stienen, 1990).

The actinorhizal *Alnus jorullensis* (syn. *A. acuminata*) is a prominent component of silvopastoral systems in high elevation areas of the Americas in both Central America and the Andean region (Dunn *et al.*, 1990). Nitrogen fixation rates from 62 to 320 kg ha⁻¹ y⁻¹ have been attributed to alders in the United States (Russo, 1990), leading to undesirable nitrate contents. Fixation may not be inhibited by high soil N concentrations (Binkley and Sollins, 1990) as with legumes (Giller and Wilson, 1991), although Danso *et al.* (1992) report inhibition of N fixation by alders when soil N contents are high. More rational utilization of this species with proven nitrogen-fixing ability has been proposed (Russo, 1990; Dunn *et al.*, 1990).

Live fences and border plantings

Traditionally, alders have been used as live fences in American agroforestry practice, but a wide range of fast-growing, easily coppiced nitrogen-fixing and non-nitrogen-fixing trees could be employed. The absence of trees on two sides of each tree permits considerable expansion of the root system, favoring conditions for nitrogen fixation (Budowski, 1983). However, the relatively small number of trees per unit area and the probable death of nodules following pruning (Nygren and Ramirez, 1995) may reduce this potential.

With the exception of live fences, most line planting of trees do not involve nitrogen-fixing trees, and the benefits of nitrogen fixation are limited to a very small area around the tree. Both the actinorhizal *Alnus* and *Casuarina* are used for windbreaks and dune stabilization, where their N₂-fixing ability may be of value in soils very low in nutrients (Giller and Wilson, 1991). Nitrogen fixation in such systems is likely to be of little environmental significance because of the small area of land occupied by the nitrogen-fixing trees.

Table 2. Soil properties (0–10 cm) under and between *Prosopis*, *Aspidoderma* and *Larrea* under grassland in the Argentine chaco (from Mazzarino *et al.*, 1991)

Vegetation/canopy position	C (g kg ⁻¹)	Kjeldahl N (g kg ⁻¹)	Extractable P (mg kg ⁻¹)	C/N	N mineralization (mg kg ⁻¹ y ⁻¹)
<i>Prosopis</i> under	19.2 a	1.82 a	39 a	10.5 c	152.7 a
<i>Prosopis</i> between	13.4 ab	1.18 bed	29 ab	11.3 be	80.1 be
<i>Aspidoderma</i> under	14.5 ab	1.20 bed	24 b	12.1 be	115.5 ab
<i>Aspidoderma</i> between	15.7 ab	1.36 be	28 ab	11.5 be	69.7 b
<i>Larrea</i> under	12.8 b	0.92 cd	32 ab	13.9 a	96.0 be
<i>Larrea</i> between	11.0 b	0.87 d	34 ab	12.7 ab	49.3 c
Grassland	18.0 a	1.45 ab	29 ab	12.4 ab	68.4 c

Values followed by the same letter do not differ significantly at $P = 0.05$ level.

NITROGEN FIXATION AND SOURCES OF NUTRIENTS IN SYNTHETIC AGROFORESTRY SYSTEMS OF THE AMERICAS

Alley farming

Giller and Wilson (1991) report no measurements of N₂ fixation in alley farming systems, but Sanginga *et al.* (1994) report that ¹⁵N labeling techniques have recently been applied to alley farming systems, and stated that more than 50% of the tree's nitrogen may be below ground after pruning. They give no figures of N fixation. The possibility of underground transfer of nitrogen to crops in this system has generally been ignored by most investigators, who have assumed that the limiting factor is the rate of release of N from tree prunings placed on the soil surface (Palm and Sanchez, 1991). Rates of nutrient release may be affected by lignin–nitrogen ratios and polyphenol content of the tree foliage. Non-nitrogen-fixing species such as *Senna* and *Gmelina* may be able to supply nutrients more readily to crops in alley farming systems (Sanchez *et al.*, 1985; Salazar and Palm, 1987). A review by Hawkins *et al.* (1990) found that crops generally responded to fertilizer, especially nitrogen, in alley farming systems. However, Salazar (1990) only found limited response when P was applied to an alley farming system of cowpeas and rice associated with *Inga edulis*, *Cassia* (*syn.* *Senna*) *reticulata*, *Gliricidia sepium*, or a mixture of *G. sepium* and *I. edulis*, a combination yielding fast- and slow-decomposing tree foliage. Studies generally showed a benefit from alley farming systems even with rapidly decomposing species such as *Leucaena* and *Erythrina* (Kang and Gutteridge, 1994). While the synchrony of nutrient release from tree prunings with the nutrient needs of associated crops is frequently difficult to obtain, long-term benefits to the total soil organic matter pool are frequently observed (Haggar *et al.*, 1993), resulting in other benefits such as reduced soil erosion (Nair *et al.*, 1995). However, J. R. Dominique (unpubl. M.Sc. thesis, CATIE, 1994) showed that in a high organic matter soil (Andic Eutropept) in Costa Rica that had been cleared from a 20-year-old secondary forest growth, when placed in alley farming with *E. poeppigiana* for 8 y, suffered a reduction in soil nitrogen contents. The reduction was less with alley

farming than with maize monoculture (Table 3). Similarly, Cooperband and Logan (1993) found considerable losses of Kjeldahl N 3 y after *E. berterroana* was introduced into native grass pastures on an Andic Humitropept, at a lower elevation in Costa Rica. A complicating matter is that litterfall is generally ignored in alley farming studies, since inputs from the tree are only measured at the time of pruning. Nygren and Ramirez (1995) showed that the litterfall might supply up to 30% of the N from the trees during a cropping cycle. The N in the litterfall might improve the synchrony between N supply and crop use, since it would be available at a later time in the crop cycle.

Rotational tree plantings

It has been suggested that the effectiveness of traditional fallows would be improved if trees were used with established soil-improving properties and value as timbertrees. Fisher (1995) published the results of a 3 y evaluation of changes in soil properties following plantings of several leguminous and nonleguminous timber trees on a Typic Tropohumult in Costa Rica with high levels of Al saturation (Table 4). Some of the trees, notably *Inga edulis* and *Acacia mangium* increased soil nitrogen levels. However, the *A. mangium* had high mortality so it was impossible to judge its effect on soil properties after the timber harvest. Harvesting trees for fuelwood would permit shorter periods of rotational fallow.

Taungya

Like line plantings, Taungya generally involves timber trees such as *Tectona grandis*, *Eucalyptus*, *Cordia* and *Gmelina*, which are not nitrogen fixing (Nair, 1993). Good results were obtained when *Acacia mangium* was associated with maize, ginger, and *Eugenia stipitata* in Costa Rica (Trejos and Von Platen, 1995). Leiva and Borel (1995) maintained maize and bean yields at almost as high amounts as the control plots over 4 y in a modified taungya system (Nair, 1993) with *Causiarina equisetifolium*, but not with *Alnus jorullensis* (*acuminata*) or *Eucalyptus globulus* (Fig. 3). It is not clear whether good performance of the associated crops can be attributed to relatively poor growth of the

Table 3. Maize yields, losses in soil N and C, gains in soil K and net profitability in 16 maize harvests in monoculture and associated with *E. poeppigiana* at different spacings on an Andic Eutropept in Turrialba, Costa Rica (calculated from J. R. Dominique, unpubl. M.Sc. thesis, CATIE, 1994)

Tree spacing	Maize yield (kg ha ⁻¹ y ⁻¹)	Loss of C from soil (kg ha ⁻¹ y ⁻¹)	Loss of N from soil (kg ha ⁻¹ y ⁻¹)	Gain (+) or loss (–) of K (kg ha ⁻¹ y ⁻¹)	Net income (\$ ha ⁻¹ y ⁻¹)
6 × 1 m	3600	1879	375	+17	–124
6 × 2 m	4000	1835	250	+5	–6
6 × 3 m	4040	2803	250	+8	+30
6 × 4 m	4400	2991	375	+20	+92
Fertilized—no trees	5000	3468	525	–15	+80
Unfertilized—no trees	2800	4378	575	–22	–166

Plots with trees received 15 kg ha⁻¹ y⁻¹ P. Fertilized plots without trees received 58 kg ha⁻¹ y⁻¹ N and 22 kg ha⁻¹ y⁻¹ P.

Table 4. Changes in soil properties following 3 y of site occupancy by nitrogen-fixing and non-nitrogen-fixing species on a Typic Tropohumult in Costa Rica (from Fisher, 1995)

Species	Kjeldahl N 1987 (g kg ⁻¹)	Kjeldahl N 1992 (g kg ⁻¹)	Organic C 1987 (g kg ⁻¹)	Organic C 1992 (g kg ⁻¹)	Olsen P 1987 (mg g ⁻¹)	Olsen P 1992 (mg g ⁻¹)	Extractable Ca 1987 (cmol kg ⁻¹)	Extractable Ca 1992 (cmol kg ⁻¹)
<i>Styphnodendron microstachyum</i>	3.1	3.1	0.75	0.76	7.2	7.9	0.86	0.88
<i>Pithecellobium macradenium</i>	3.2	3.2	0.76	0.77	6.0	5.5	0.45	0.98*
<i>Inga edulis</i>	3.0	3.4*	0.74	0.74	5.2	7.2*	1.12	0.83
<i>Acacia mangium</i>	3.0	3.3*	0.73	0.77	7.3	8.1*	1.27	1.52*
<i>Pentaclethra macroloba</i>	3.0	3.0	0.73	0.72	7.4	7.0	1.28	1.15
<i>Vochysia guatemalensis</i>	3.3	3.3	0.74	0.82*	4.8	7.9*	1.04	0.99
<i>Gmelina arborea</i>	3.3	3.1	0.78	0.76	4.9	4.6	1.19	1.36*

associated trees. No measurements of nitrogen fixation in such systems have been made, although relatively high fixation rates have generally been reported for *A. jorullensis* and *C. equisetifolia*.

Protein banks and other improved silvopastoral systems

Protein banks commonly are solid plantings of leguminous trees or shrubs that are repeatedly pruned for animal feed. Because of the constant removal of biomass, the system should be stressed to fix considerable quantities of nitrogen. Leguminous trees have frequently been interplanted with nonleguminous pasture species as a possible source of nitrogen (Fassbender, 1993; Libreros *et al.*, 1994). An association of *Erythrina poeppigiana* and king grass (*Pennisetum purpureum* × *P. typhoides*) resulted in higher extraction of nitrogen and magnesium by the king grass, although production remained constant whether none, 1/3, 2/3 or all of the *Erythrina* prunings were applied to the soil. Extraction of potassium by the king grass proved a major limitation to the system. When all the *Erythrina* foliage was deposited on the soil surface, it contributed 266 kg ha⁻¹ y⁻¹ of N but only 145 kg ha⁻¹ y⁻¹ of K, while the 20 t ha⁻¹ y⁻¹ of king grass produced by the system contained 376 kg of N and 767 kg of K. Thus, K became more limiting than N. In another experiment on the CATIE farm in Turrialba, Costa Rica, production of stargrass (*Cynodon plectostachum*) was 11.7, 16.9 and 18.2 t ha⁻¹ y⁻¹ without trees, associated with *Erythrina* and associated with *Cordia*, respectively (Fassbender, 1993). Since the *Erythrina* prunings were removed in the latter study, this might be some evidence for underground transfer of nitrogen. The fact that *Cordia* gave as high pasture production as *Erythrina* may, however, indicate that water relationships from shading, rather than nitrogen fixation, caused higher pasture production under trees.

Recently, a combined production system has been developed at CATIE in which *Erythrina* is associated with the non-nitrogen-fixing *Morus* spp. and king grass. *Erythrina* is pruned periodically and the foliage applied to the soil. Goats are fed a com-

bination of only the king grass, *Morus* spp., mineral salts and water. The goat manure is applied to the shrubs and grass associated with *Erythrina*. Over 3 years, 1200 m² that contained 800 trees of *Erythrina beteroana* and two goats supported production of an average of 12000 kg of milk y⁻¹ with the mineral

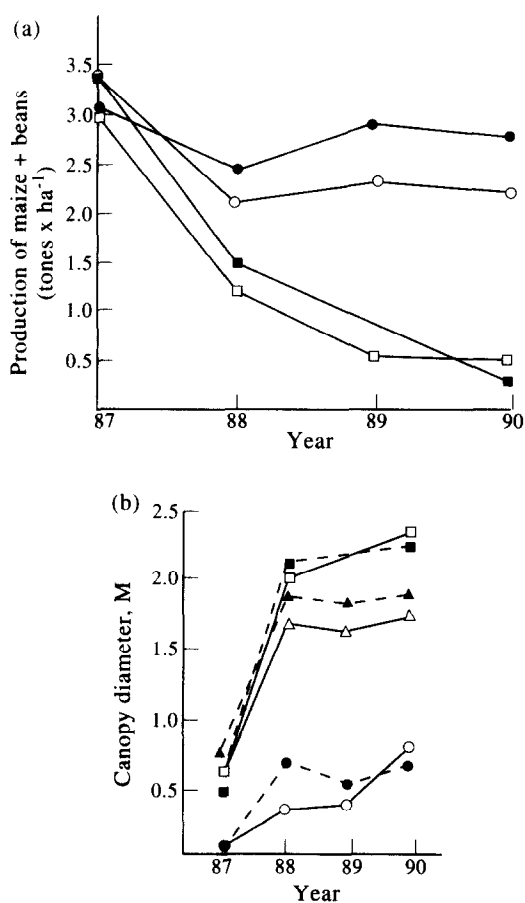


Fig. 3. Yield of maize and beans (a) and tree canopy diameter (b) in a modified taungya system using *Casuarina equisetifolia*, *Alnus jorullensis* (*acuminata*) and *Eucalyptus globulus* (from Leiva and Borel, 1995). Symbols for a: ● sole crop; ○ *Casuarina equisetifolia*; ■ *Alnus acuminata*; □ *Eucalyptus globulus*. Symbols for b: □ *Alnus* pure stand; ■ *Alnus* associated; △ *Eucalyptus* pure stand; ▲ *Eucalyptus* associated; ○ *Casuarina* pure stand; ● *Casuarina* associated.

salts fed the goats as the only input from outside the system. Profit was \$4800 ha⁻¹ y⁻¹ if labor was paid and \$15080 if family labor was used (Oviedo *et al.*, 1994). The principal input of nitrogen to the system was the *E. berteriana*.

CONCLUSIONS

There are a great number of agroforestry systems in the Americas in which biological nitrogen fixation is of considerable significance. Few of these systems have been studied in sufficient detail to quantify either the area they occupy or the amount of nitrogen being supplied by biological fixation. Nitrogen-fixing trees are an important component of the production systems for coffee and cacao, two very important cash crops. The tendency in recent years has been to neglect the importance of biological nitrogen-fixation in these systems, to remove nitrogen-fixing trees from coffee plantations and pastures, and to substitute mineral fertilizers with unknown environmental consequences. It is possible to maintain the productivity of these areas with nitrogen-fixing trees as a nitrogen source. Research is needed to establish the role of the nitrogen-fixing trees in sustainable management practices for these systems.

Acknowledgements—The authors would like to thank Avilio Franco for suggesting a topic on which much information was available that had never been properly summarized, John Beer for many suggestions about what to include in the review, and Robert Burris for his considerable editorial contribution.

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